Electronic Scanning Antennas for Amateur Spacecraft

Tom Clark, K3IO (ex W3IWI)

k3io@verizon.net or k3io@amsat.org

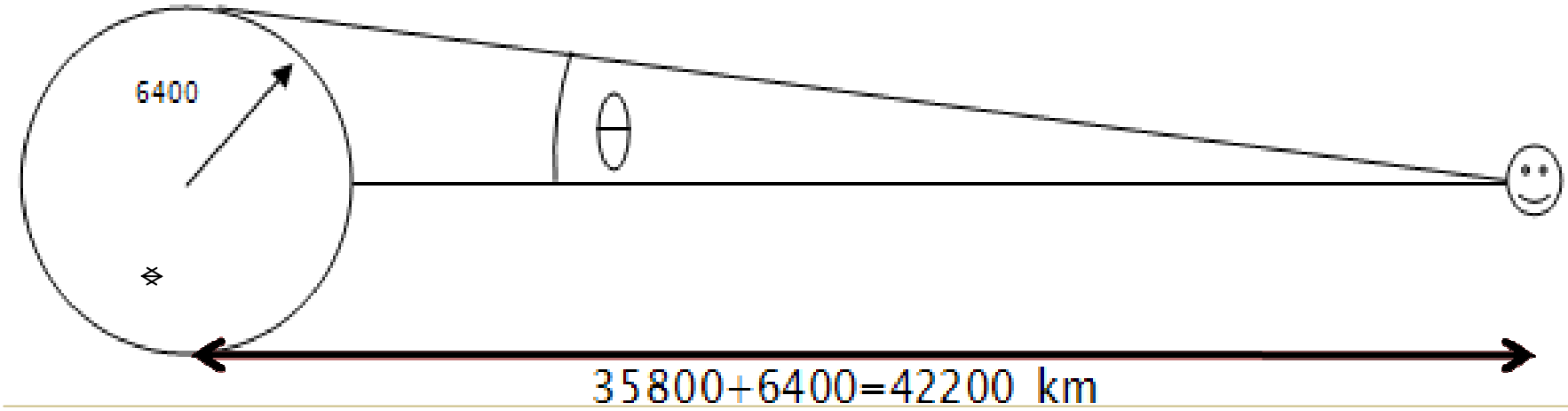
AMSAT Space Symposium
Pittsburgh, PA
October 27, 2007

The Basic Problem

- Because of ~200 dB path losses, HEO satellites require either
  - Huge TX power at the spacecraft, *and/or*
  - Huge user antennas on the ground, *and/or*
  - ~ 22 dBi of antenna gain at the spacecraft.
- In order to get this antenna gain, we need
  - A fixed dish with active mechanical pointing of the S/C or antenna, *or*
  - **An electrically steerable antenna array that has no moving parts.**

SLOW
SCIENTISTS
CROSSING

How Much Gain is Needed ?



The angle **Θ** will then be

$$6400/42200 = 0.152 \text{ radians} = 8.7^{o}$$

The solid angle **Ω** that is subtended by the earth (as seen from the satellite) is a disk with an area

$$\Omega = \pi\Theta^{2} = 0.0726 \text{ steradians.}$$

And in antenna terms, this means we need a Directivity D….

$$D = \left[\frac{4\pi}{\Omega}\right] = \text{a factor of } 173.1 = 22.4 \text{ dBi}$$

- Directivity does not account for Ohmic losses, so the real gain G is reduced by the efficiency η like

$$G = \eta D, \text{ where } \eta < 100\%$$

- Hopefully, we will achieve $\eta \geq 50\%$, so the real-world Gain will be > 19 dBi

The Directivity **D** is related to the collecting area of an antenna by

$$D = \left[\frac{4\pi A}{\lambda^2}\right]$$

In the Symposium proceedings, I show this table that relates D=22.4 dBi to the size of a uniformly illuminated antenna aperture:

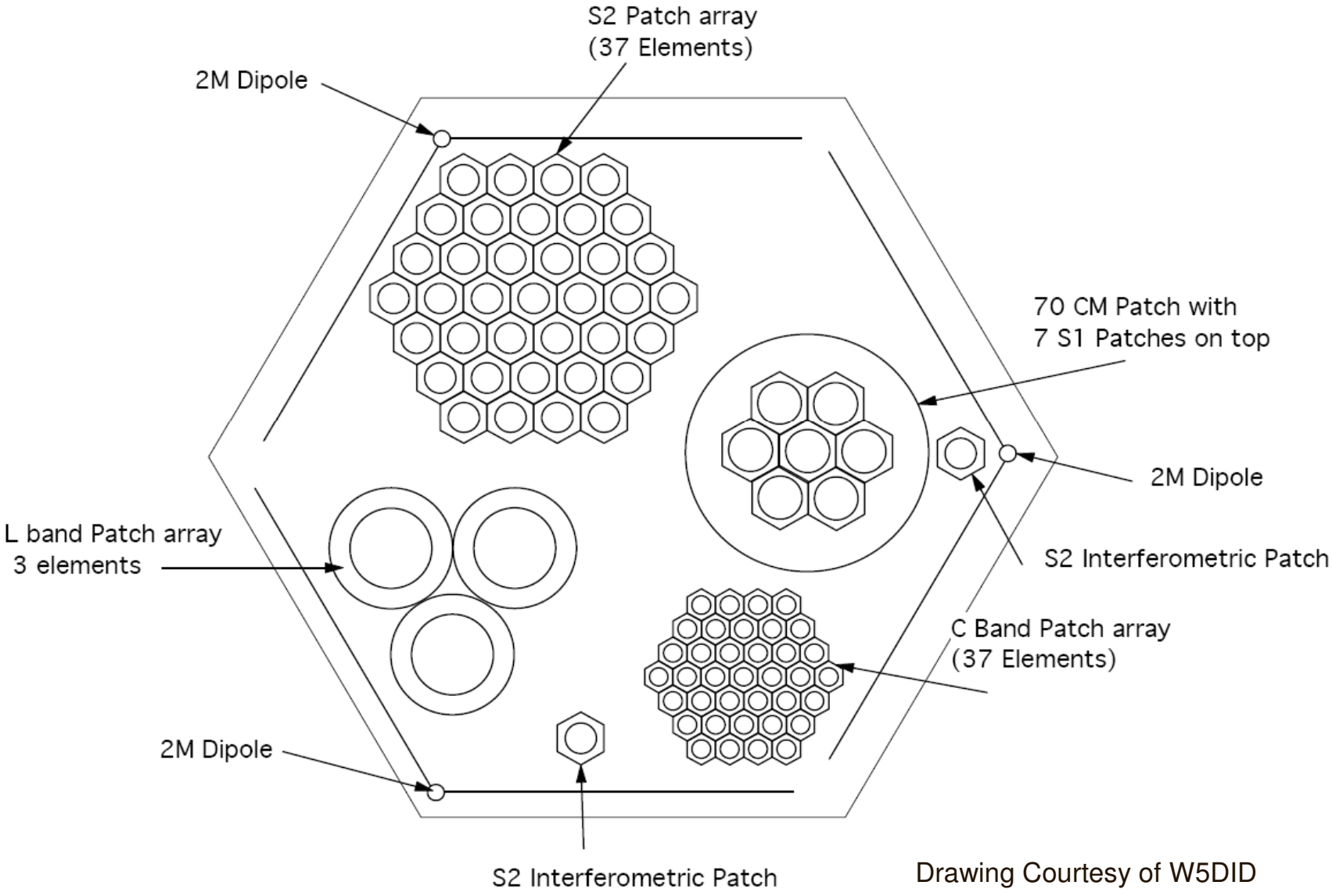
Frequency	Wavelength λ	Collecting Area for D=22.4 dBi	Characteristic Size = $\sqrt{A}$	Equivalent Dish Diameter
L = 1.27 GHz	23.6 cm	7672 cm²	87.6 cm	112 cm
S1 = 2.4 GHz	12.5 cm	2152 cm²	46.4 cm	59.1 cm
S2 = 3.4 GHz	**8.82 cm**	**1072 cm²**	**32.7 cm**	**41.6 cm**
C = 5.7 GHz	**5.26 cm**	**381 cm²**	**19.5 cm**	**24.8 cm**
X = 10.5 GHz	2.86 cm	113 cm²	10.6 cm	13.5 cm

Table 1 : 22.4 dBi Antenna Sizes for Microwave Frequencies

Arrays -- getting D=22.4 dBi

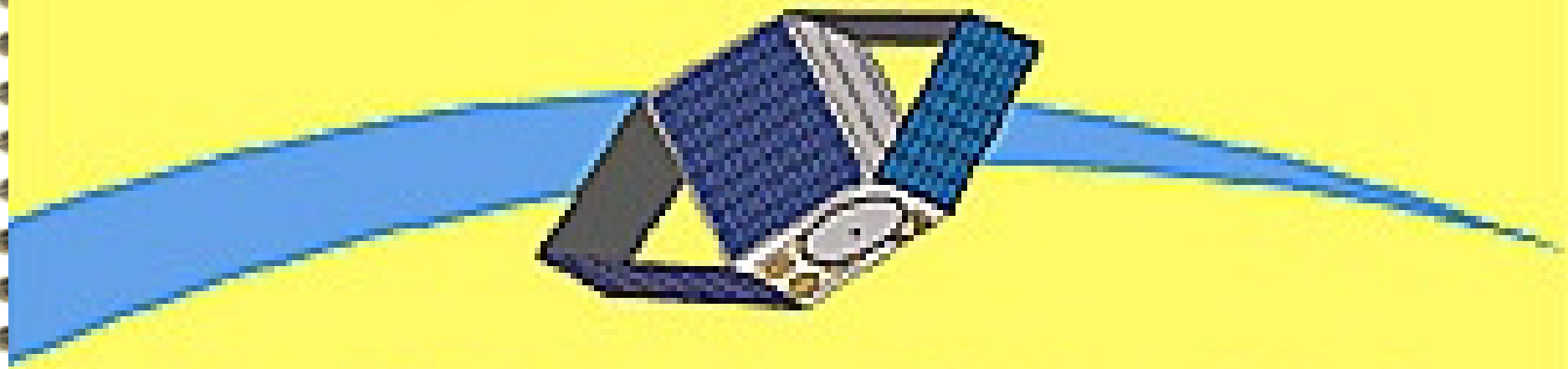
- An N-element phased array on TX can make use of a distributed Power Amplifier (PA) to achieve high power
  - A 40 watt TX could be built from 40 individual one watt PAs
  - The failure of a few PAs is not catastrophic
- Individual patch antennas have a typical gain ~ +6.5 dBi
- With 6.5 dBi patches, we need the array to provide ~16 dBi gain. This in turn requires an array of N ≈ $\log_{10}(16/10)$ ≈ 40 elements.

On EAGLE, the antennas might look something like this (N=37):



Drawing Courtesy of W5DID

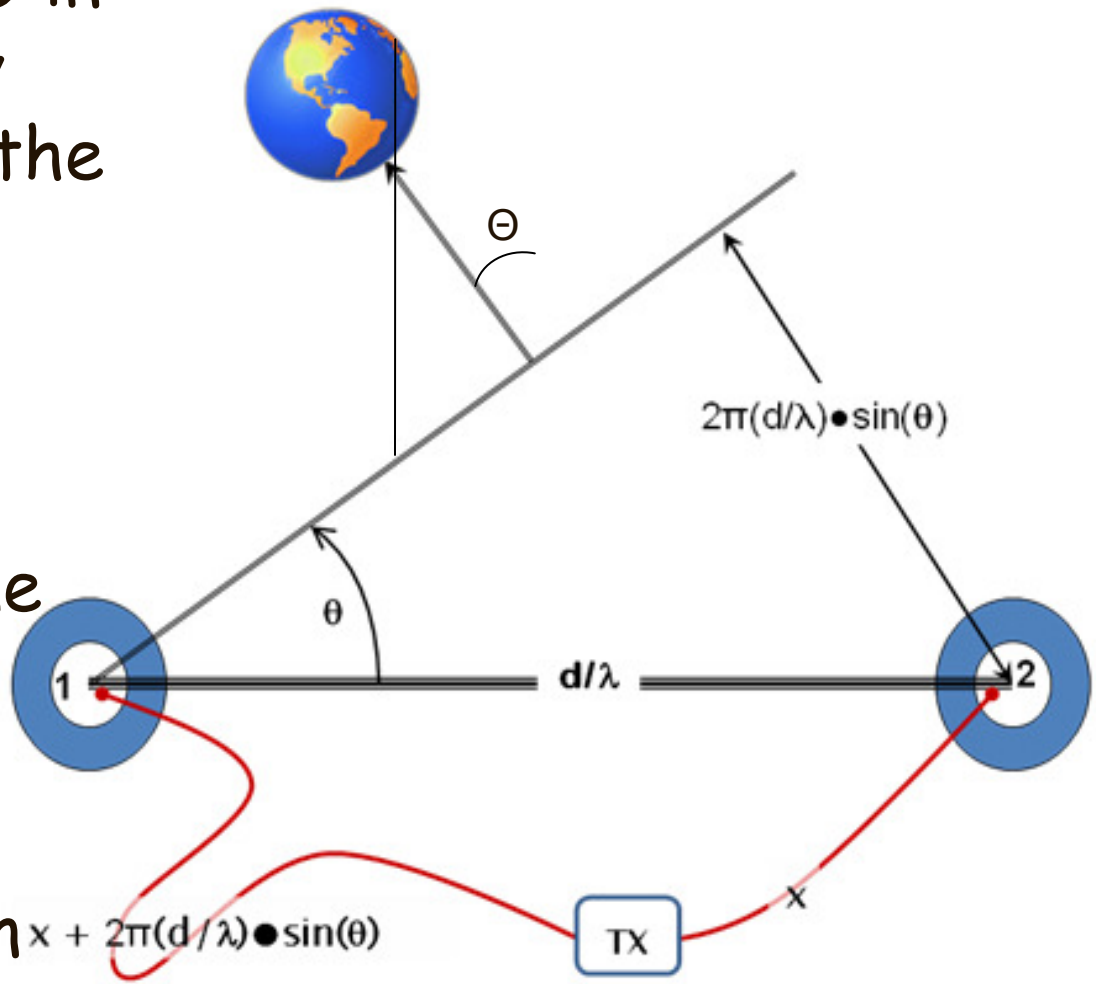
AMSAT



We ARE Rocket Scientists!

The 2-element interferometer: **The key to a phased array**

1. Measure the angle **Θ** in the plane formed by the 2 elements and the target earth. Note that Θ is the conventional off-pointing angle.
2. Measure the baseline as **d/λ** wavelengths.
3. The signal from element #1 must be delayed by adding an extra phase shift of **$(2\pi d/\lambda)\cdot\sin(\theta)$** to match the signal from element #2



Interferometers and the concept of Spatial Frequency

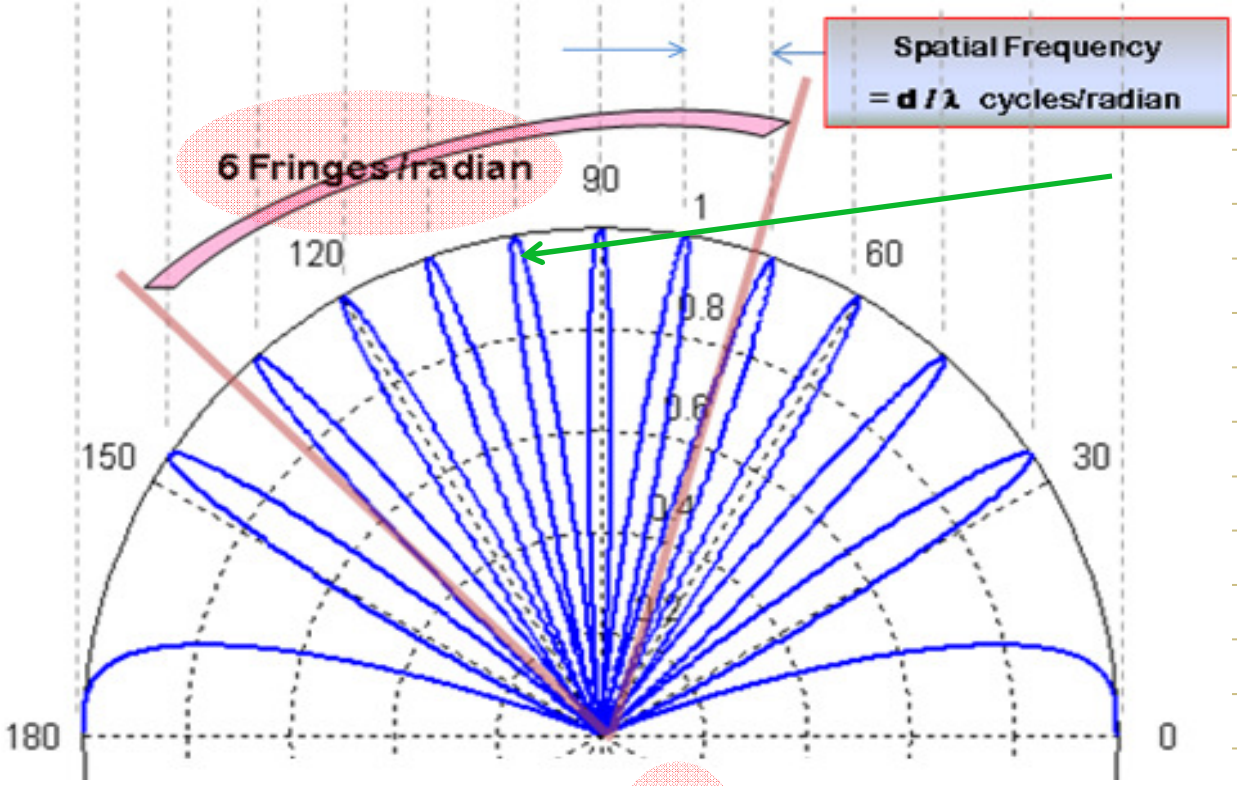
- Let's QSY & think about the receiving case.
- Let a source drift thru the pattern of a 2-element interferometer.
- The output is a sine wave of the form

$$V(\theta) = \cos\left[(2\pi d/\lambda)\cdot\sin(\theta) + \varphi \right]$$

where φ is a constant "DC" phase shift.

- This sinusoidal pattern is frequently called "fringes".

An Interferometer with a 6λ Baseline



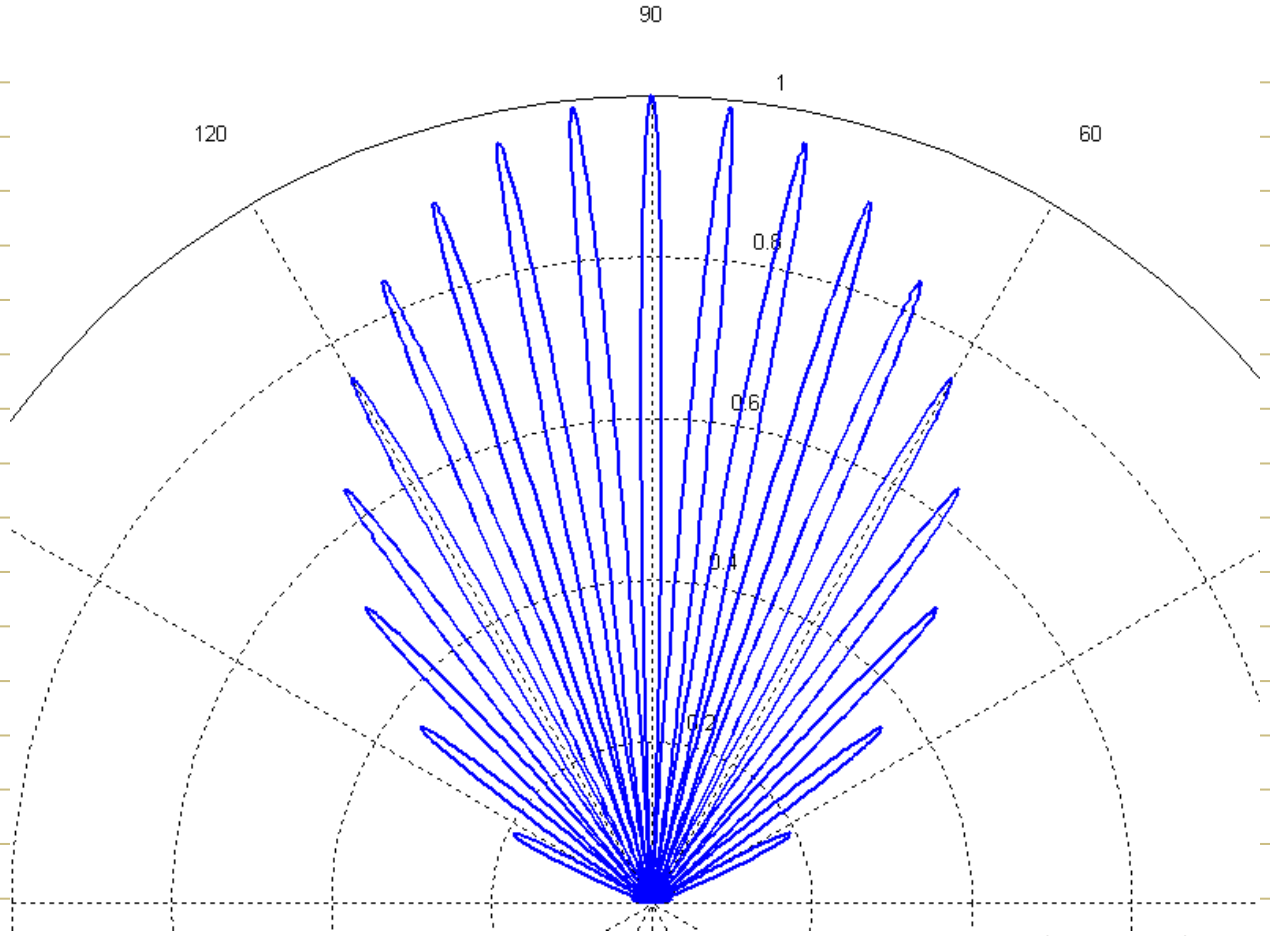
The instrumental phase constant φ has been set so that the central lobe is at the zenith.

Isotropic elements provide uniform response of the entire sky.

$$V(\theta) = \cos\left[(2\pi \cdot 6) \cdot \sin(\theta) + \varphi \right]$$

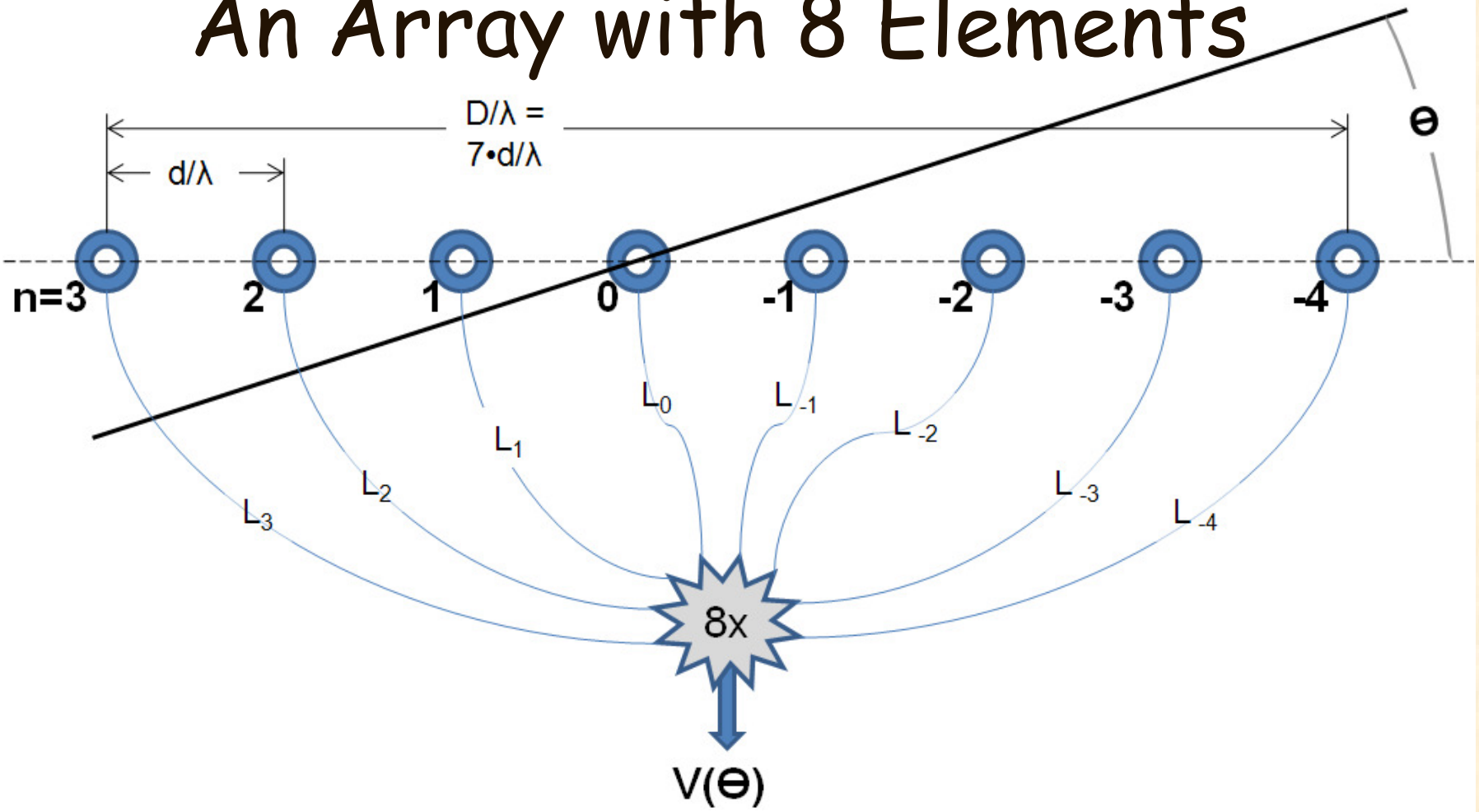
Because the interferometer is d = 6λ long, it produces a *spatial frequency* of 6 fringes/radian on the sky.

An Interferometer with a 10λ Baseline



A 10 λ interferometer with dipole elements reducing the pattern at the "horizon". Since d/λ=10, there are 10 fringes/radian.

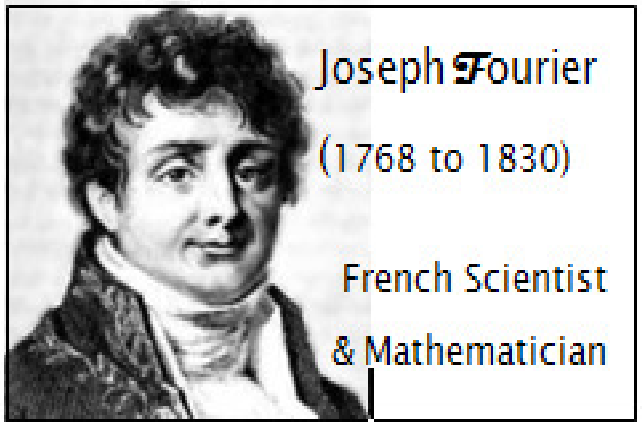
An Array with 8 Elements



Each L_n feedline needs to be longer than its right-hand neighbor by $d \bullet \sin(\Theta)$. Then add the signals to get:

$$V(\Theta) = \sum_{n=-4}^{n=3} Vn \bullet \cos 2\pi\left[\frac{d \bullet n}{\lambda} \bullet \sin(\theta) + \frac{Lo}{\lambda}\right]$$

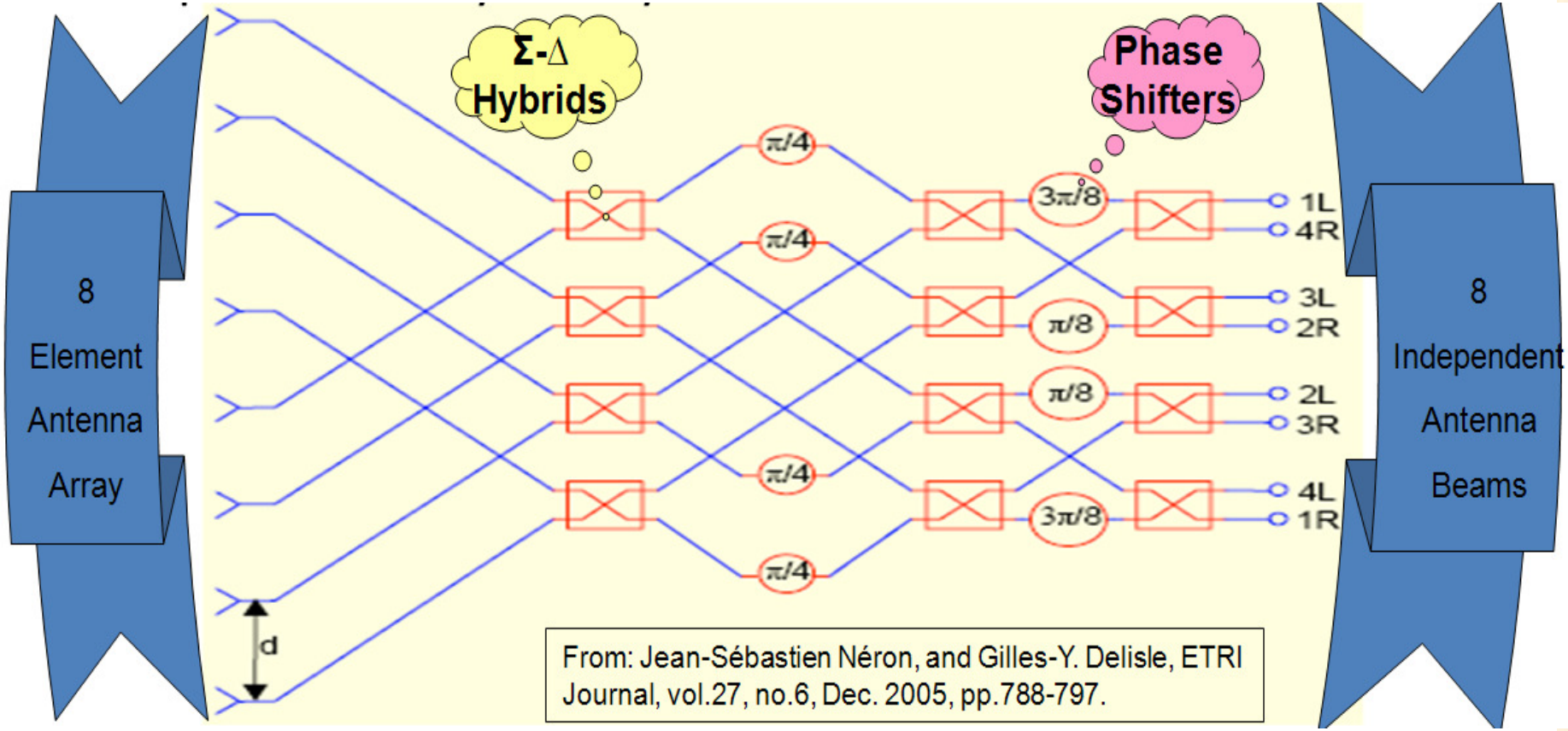
Joseph Fourier's contributions to antenna arrays.



Fourier (& his friends)	"Frequency" Domain	Time/Angle Domain
"Signal" Series	V(f)	V(t)
Spectral Components	$V(\frac{d}{\lambda})$	V(Θ)

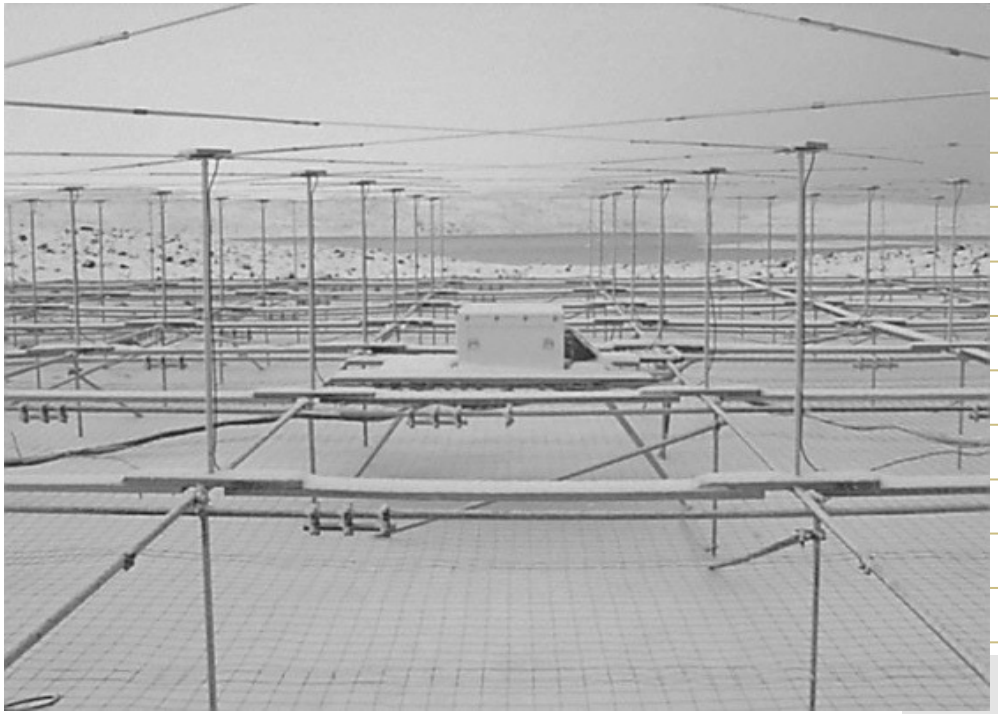
- Just as {*Time History/Frequency*} are related by a **Fourier** transform in signal analysis, {*Antenna Pattern/Spatial Frequency*} are similarly related.
- For a **2D** antenna aperture, we need to use a **2D Fourier** transform for analyzing a typical antenna.

The Butler Array is a hardware version of the Cooley-Tukey FFT algorithm



FFTs (and Butler Arrays) are best done with 2^n elements and antenna beams.

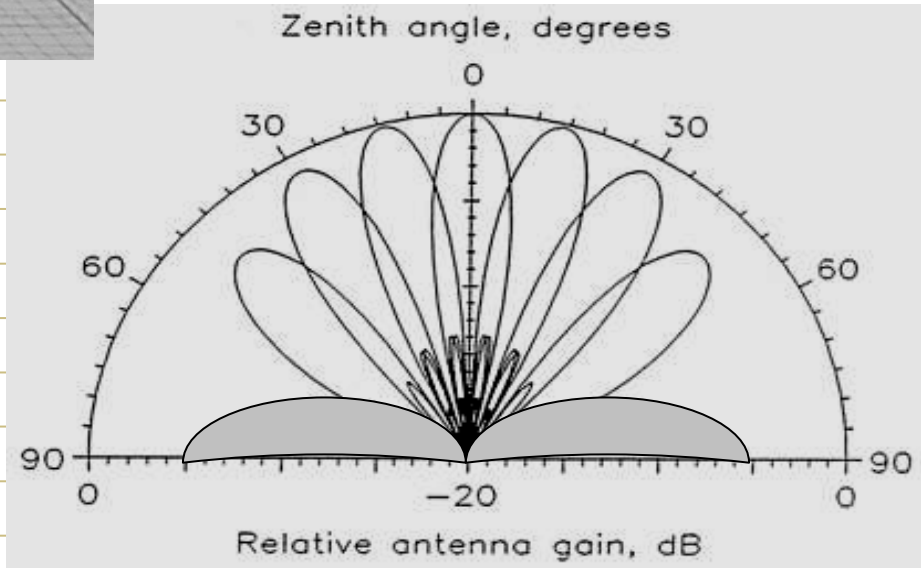
SHIRE – an 8x8 Dipole Array



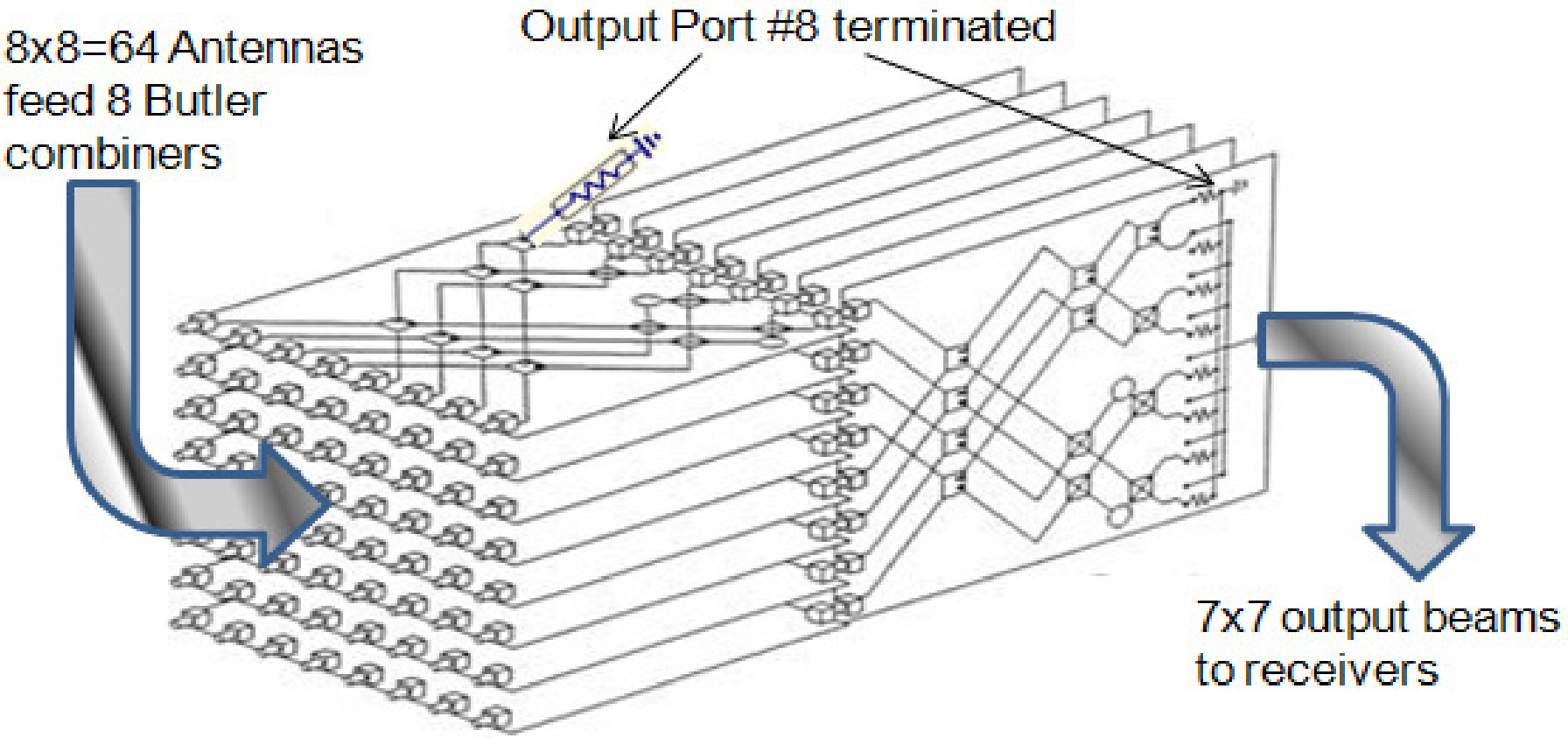
SHIRE is an acronym for the ***S**outhern **H**emisphere **I**maging **R**iometer **E**xperiment* at the Australian Davis station in Antarctica.

SHIRE consists of 8x8 λ/2 dipole arrays in each of 2 polarizations.

The pattern of an 8-dipole row is shown here.

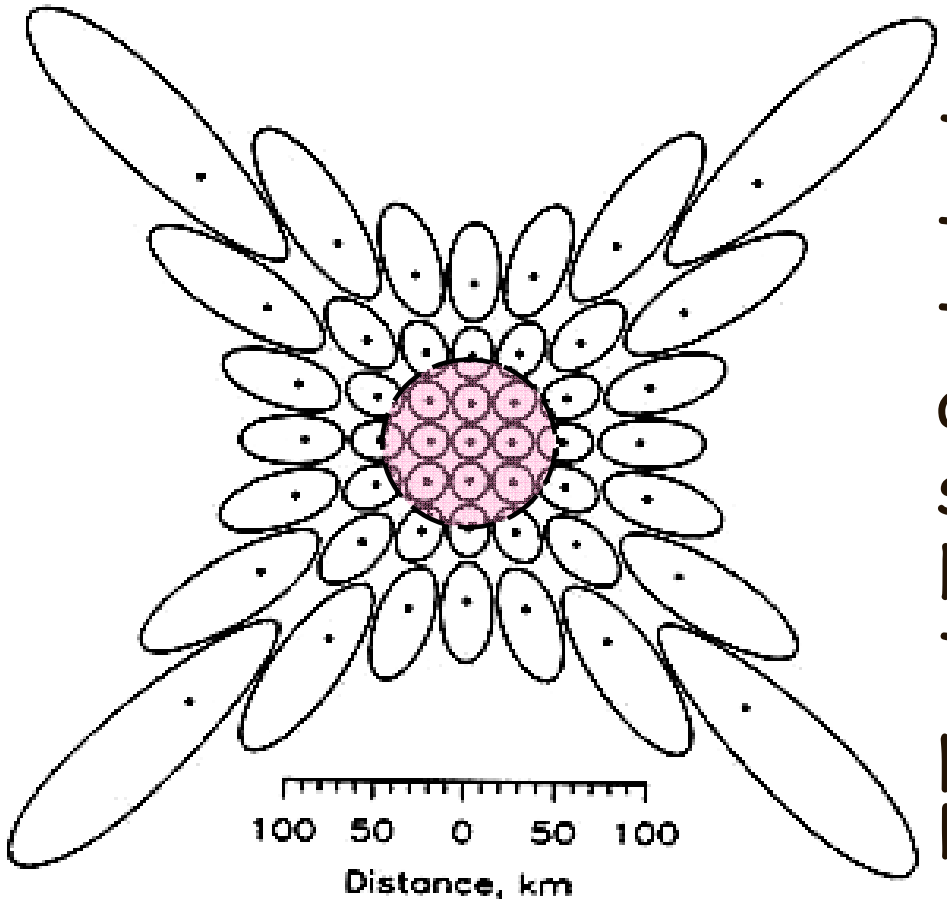


SHIRE's 2D Butler Matrix



Each row of 8 antennas feeds the combiner shown earlier. 7 lobes on the sky are used, and the horizon lobe is terminated. The 7 "sky" beams feed 7 more Butler combiners to yield 49 2D beams on the sky.

The 49 Beams of Shire



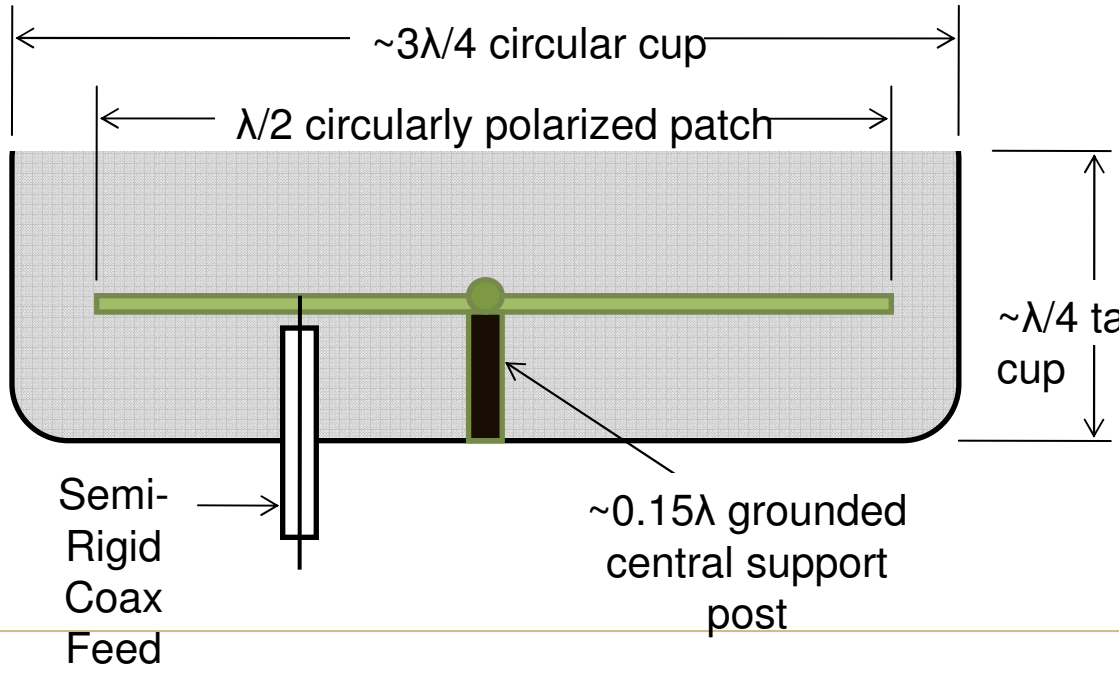
This illustration shows the -3dB contours of the 49 resulting beams as projected onto the sky at the 90 km height of the D-region. The dots show the peak response of each beam.

More details about SHIRE can be seen at http://www.ips.gov.au/World_Data_Centre/1/6/2

Now let's look at the Eagle/P4 Lite Microwave Antenna Farms:

For the microwave frequencies, the use of patch antennas is logical.

- Mechanically simple & rugged
- ~ 6 dBi gain for each patch is reasonable
- A circular λ/2 patch is placed in "cup" that is about ~λ/4 deep and ~3λ/4 in diameter.



The cup acts a a single choke ring to improve the gain by reducing the response at the horizon. It also serves to reduce element-to-element coupling.

Some N~40 Array Geometries (1)

N=36 Square
$9.00

*This geometry looks good and is simple to analyze, but it would be **very** complicated to implement two dimensional phasing.*

N=37 Heaxgon
$9.25

The hexagonal arrangement packs the maximum number of elements into the minimum possible space. I have not been able to devise a simple 2-D feed scheme.

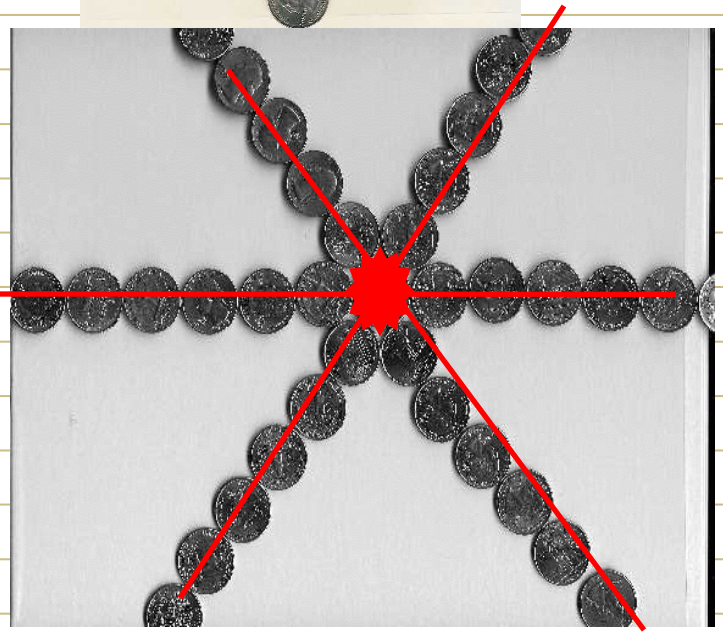
Some N~40 Array Geometries (2)

N=43 Extended Hex
$10.75

The hexagonal arrangement still packs the maximum number of elements into the minimum possible space. I have not been able to devise a simple 2-D feed scheme.

N=37 6-Armed Star
$9.25

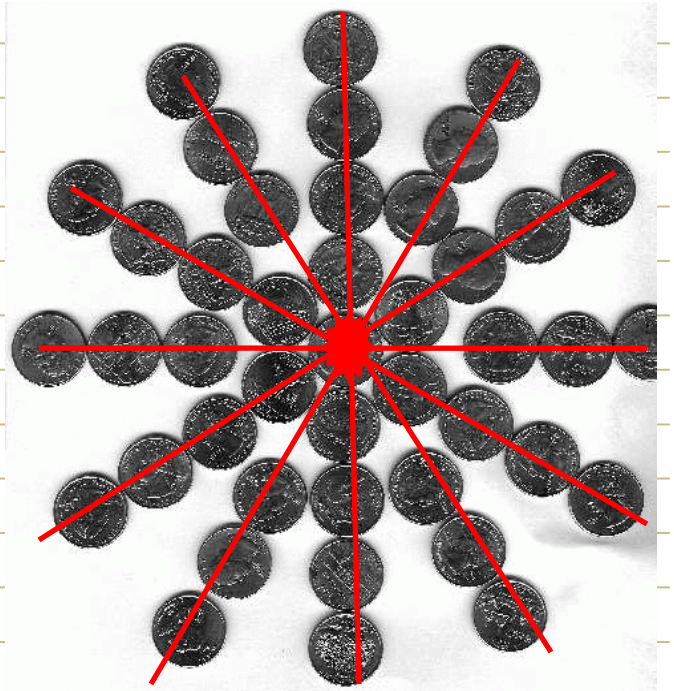
This design is the easiest to feed because the elements are equally spaced along a few straight lines. However, this arrangement will have higher sidelobes than desired because it is too loosely packed. It also makes very inefficient use of the available real estate.

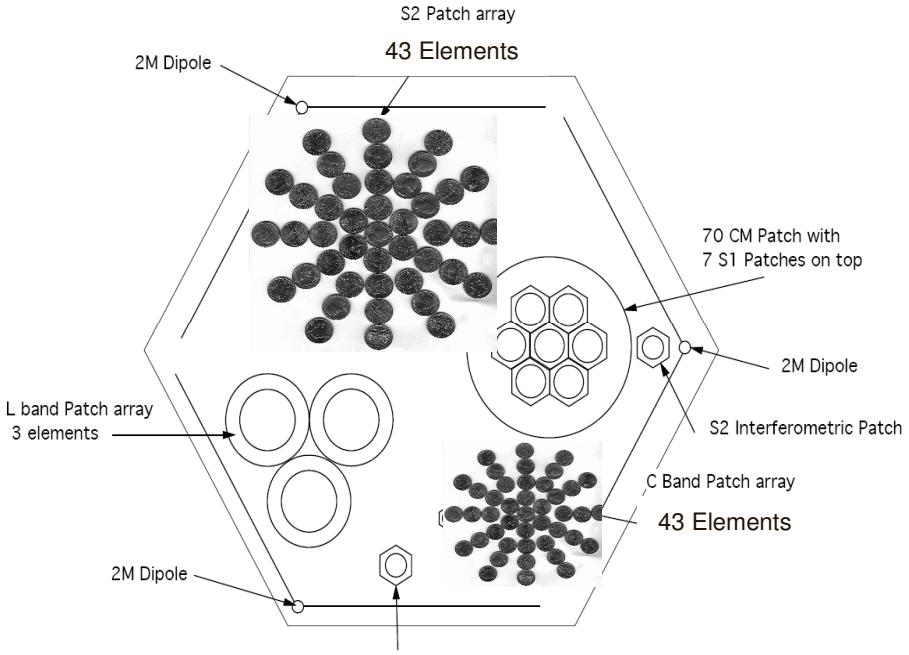


Some N~40 Array Geometries (3)

N=43 Extended Star
$10.75

This is an extension of the Star packs more elements, with a better pattern. With all the elements distributed along straight lines, the phasing to accomplish beam steering is relatively simple.



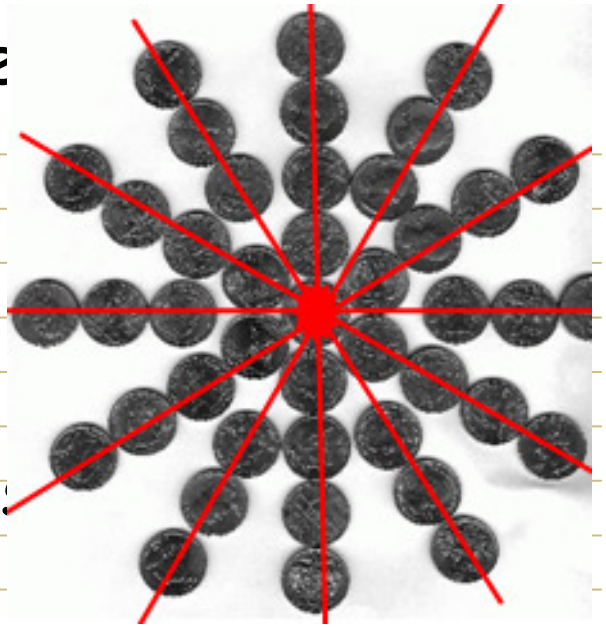


N=7 Sand Casting

In the text is Table 2, which summarizes factoids about each of these geometric shapes.

Parameter	S2 (λ=88 mm)	C (λ=53 mm)	$0.25 coins (24mm diameter)
Required Array Real Estate = 3.75 – 5 λ in size (depending on shape)	330 – 440 mm	200 – 260 mm	n = 36 to 43 costing me $9.00 -- $10.75
λ/2 Patch Diameter	44 mm	26 mm	--
λ/4 Cup Height	22 mm	13 mm	--
3λ/4 Cup Spacing	66 mm	40 mm	24 mm
0.15 λ Central Support Post	13 mm	8 mm	--
15a: 6x6 Element Square	396 x 396 mm	240 x 240 mm	$9.00
15b: n=37 Hexagon	~460 mm diameter	~280 mm diameter	$9.25
15c: n=43, Extended Hex	~500 mm diameter	~305 mm diameter	$10.75
15d: n=37, 6-armed Star	~860 mm diameter	~520 mm diameter	$9.25
15e: n=43, 12-armed Star	~595 mm diameter	~360 mm diameter	$10.75
"Perfect" Dish (η=100%)	415 mm diameter	250 mm diameter	--

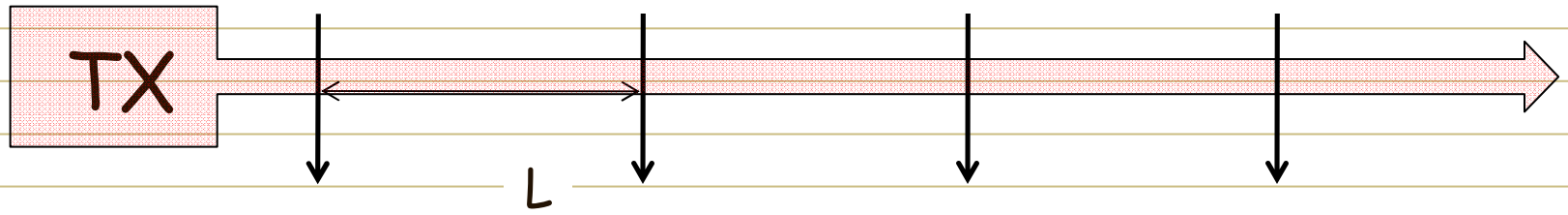
Why I favor the STAR geometry



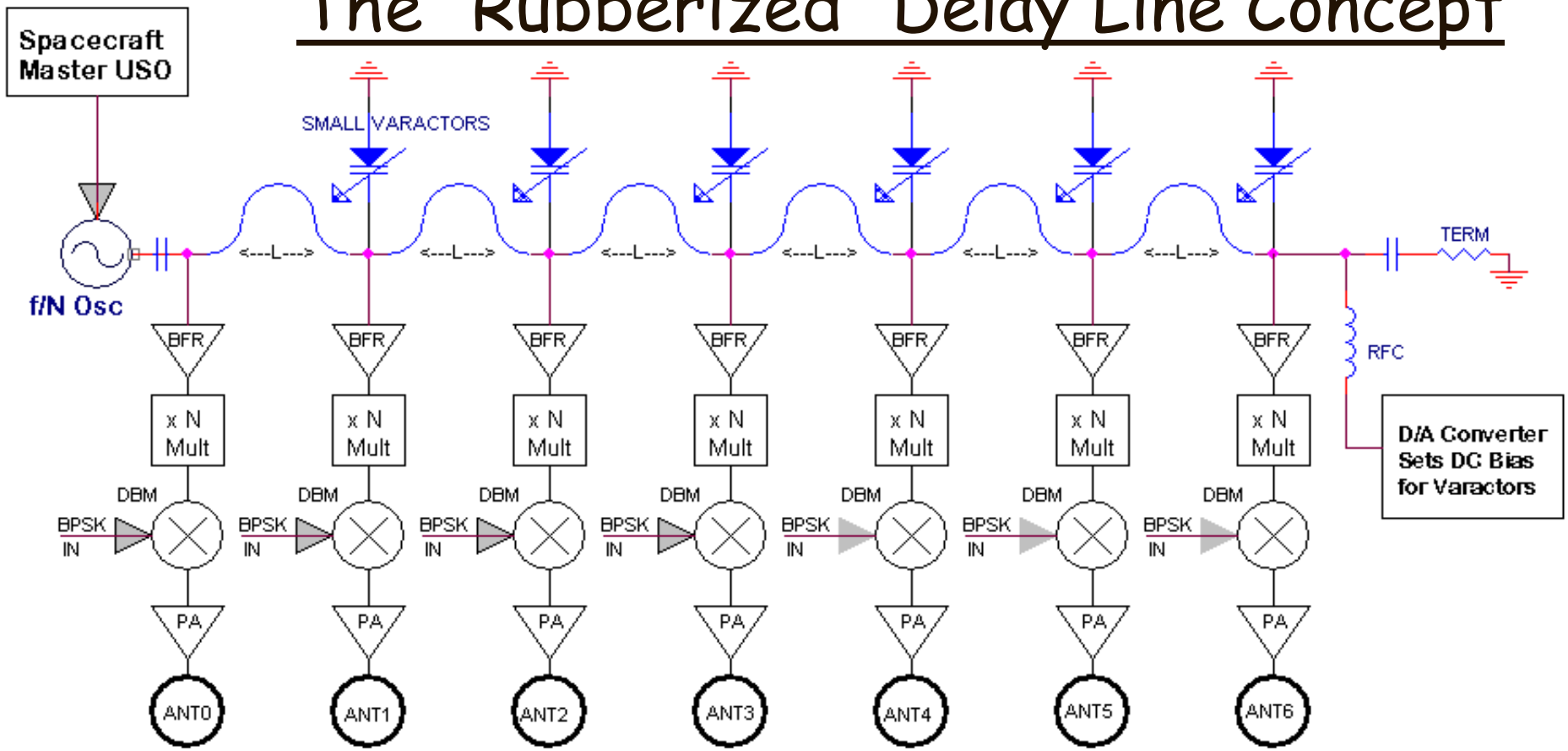
Along any of the red lines, we have a linear array with equally spaced elements. To phase such an array we have the simple geometrical relation that the required phase shift between adjacent elements is $\{2\pi \cdot [d \cdot \sin(\Theta_{ARM}) + L] / \lambda\}$, where Θ_{ARM} is measured in the plane containing the arm (red line) and the target (Earth), and where L is the (electrical) length of the delay line connecting the elements.

Note that each of the 6 lines has a different value for the angle Θ_{ARM} and that, as the spacecraft spins, the angle changes at the spin rate.

A Tapped Delay Line

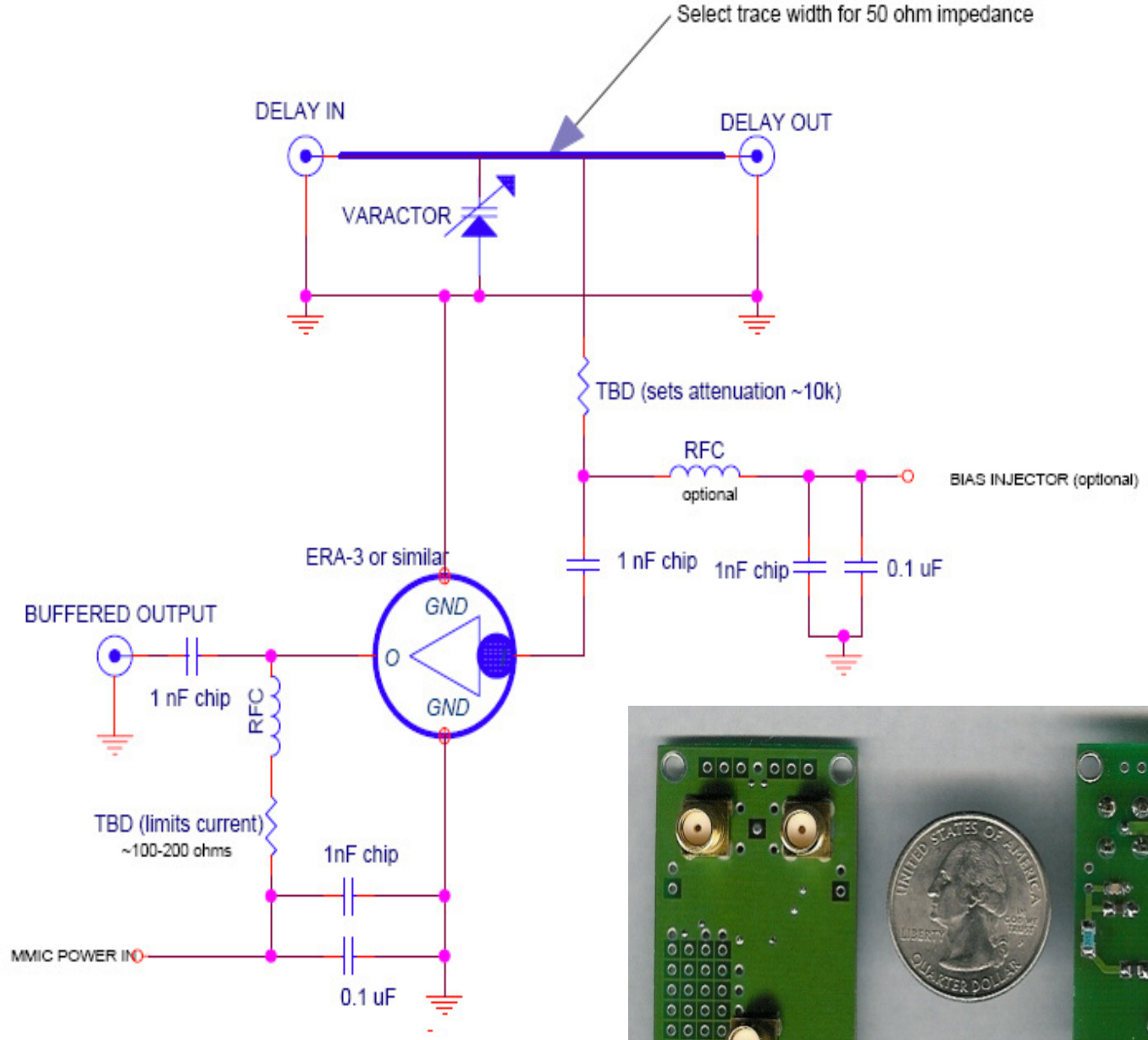


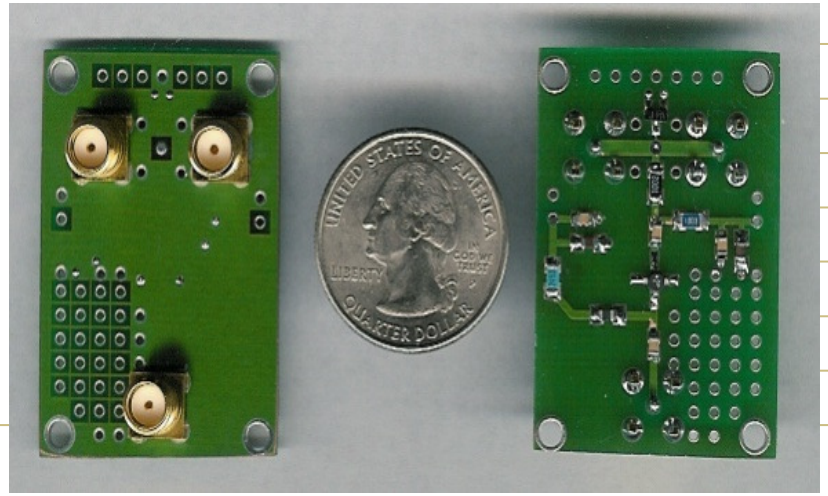
The "Rubberized" Delay Line Concept



The delay line is tapped at uniform intervals L. It is lit up with a signal at some convenient VHF/UHF freq. f/N that is a sub-multiple of the desired TX output. A small varactor at each tap, driven by a DC bias from a D/A, acts as a programmable phase shifter.

The Delay Line "Pod" Test Fixture



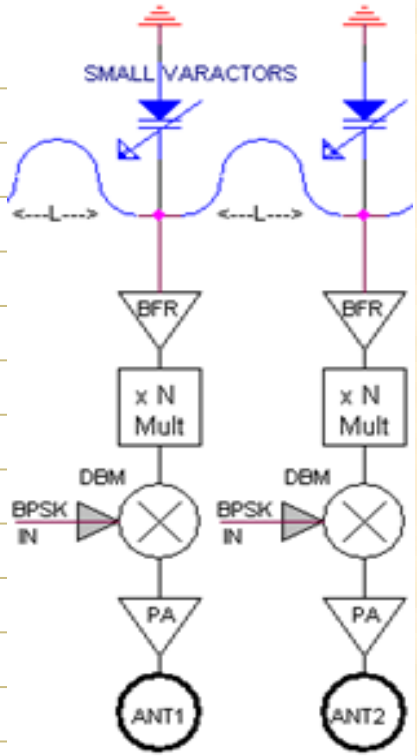


HOW ABOUT BANDWIDTH? DON'T WE NEED MULTIPLE DELAY LINES FOR THE BPSK MODULATING SIGNAL TOO?

- The answer is a simple NO ! ! !
  - Consider that we have a total signal bandwidth of B; this makes the minimum wavelength handled by the array be $\lambda_{min}=c/(f+B/2)$ and the maximum be $\lambda_{max}=c/(f-B/2)$.
  - The difference in phase shift between max & min will be small as long as the array is small compared with the wavelength associated with the signal bandwidth -- i.e. **(Array Size) «** $\lambda_{mod} = c/B$.
  - The total bandwidth permitted to the amateur satellite service at C-band is 20 MHz (λ_{mod}= 15m) & S2 is only 10 MHz wide.

HOW ABOUT USING A PHASED ARRAY FOR RECEIVE?

- Everything we have described is equally applicable to the receiving case.
- In the "Rubberized" Delay Line, we would use an f_{RX}/N VHF signal at its N^{th} harmonic to generate a Local Oscillator (LO) signal.



- The balanced mixer would be used to down-convert the RF signal to a convenient IF, and the power amplifier role would be reversed as an Low-Noise amplifier (LNA).

AND IN CONCLUSION

While the phased array concept may initially seem complex, I believe that the use of microwave phased arrays actually leads to a simplification of design of a spacecraft like Eagle. Some of my reasons for making this statement are:

1. If no pointing is provided for a large (gain > 20 dB) antenna on a spacecraft, the beam restricts usage to a small part of a spacecraft's orbit.
2. As amateurs, we face a problem in trying to mechanically point a large antenna, either by gimballing the antenna or making the spacecraft itself be 3-axis stabilized.

AND IN CONCLUSION (2)

3. A phased array offers the possibility of pointing a large antenna by moving electrons and not mass. This task is within the grasp of low-cost amateur technology!
4. On the transmit side, each of the N elements of an array can include a (relatively) small power amplifier. For the cases in this paper, about ~40 antennas each have a ~1 watt PA to yield ~40 watts of transmitter power.
5. With the power amplifier distributed to each antenna, the isolated failure of a few elements will do little to degrade spacecraft performance.

AND IN CONCLUSION (3)

6. The heat loading of the PA devices is distributed across the entire array area. The individual patch antennas and their "choke ring" cups provide additional heat radiating area.
7. Individual transmitter elements could be turned off to save power and/or spread or shape the beam. Turning off ½ of the elements drops the transmit power by 3 dB and decreases the antenna gain by 3 dB, providing 6 dB of power control. A spacecraft in elliptical orbit could make use of these capabilities to further extend useful operation as the spacecraft approaches perigee.

AND IN CONCLUSION (4)

8. We have presented a (relatively) simple phasing scheme which enables proper phasing of elements that are uniformly spaced along a line. This steering involves the use of a varactor-loaded delay line tapped at uniform intervals (figure 16). The varactors can be "tuned" with a simple D/A converter driven by the spacecraft computer. This paper describes (figure 15e) an array geometry that appears to optimize performance while minimizing complexity.
9. The same concepts can be applied to generate phase local oscillator signals for a phased receiving array.

73 de Tom, K3IO